Mechanical and durability screening test methods for cylindrical CFRP prestressing tendons

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Abstract

Concrete prestressed with carbon fibre reinforced polymer (CFRP) tendons beneficially utilises the strain capacity and durability characteristics of the CFRP material. However, changes to CFRP tendon material formulations or production processes present a challenge when building up a body of knowledge to assess the long-term behaviour of a prestressed concrete system. Designers either need to be confident that existing results can be mapped across to new systems or a programme of testing is required to provide indicators of future performance.

A series of qualification tests suitable for pultruded uni-directional cylindrical tendons were assessed using CFRP tendons with three different resin systems. Tendon samples were also exposed to wet environments to evaluate the longer-term solution uptake and associated mechanical durability implications. While characterisation measures such as the glass transition temperature, optical images and moisture uptake provided comparative results, the correlation with mechanical properties obtained from uni-axial tension, double notch shear

and torsion tests was unclear. Using a sub-set of the thermo-mechanical test protocols, a retrospective analysis of CFRP tendons extracted from a prestressed concrete lighting pole under sustained load for 16.5 years was also undertaken.

Subject Headings: Composite materials, Test procedures, Durability, Stress

1.0 *Introduction*

Much of our civil infrastructure requires design lives of 50+ years. For prestressed concrete applications, high strength, high stiffness and durable reinforcing materials are necessary. Advanced composite carbon fibre reinforced polymer (CFRP) tendons offer a number of advantages over more traditional steel prestressing tendons. One of the strengths, and also the weaknesses, of CFRPs is that there are a multitude of variables that can be modified in order to achieve particular material properties. The use of different fibres, matrices, processing methods and parameters, surface finishes or coatings will all lead to different product outcomes. Fibre, resin and composite product systems are generally proprietary and end users often have little control over the implementation of changes in the material formulations even though these changes may impact the intended performance of the supplied materials. Yet, it is perhaps almost inevitable that products will change with time as a result of drivers such as material developments, economics and sustainability.   This presents an obstacle in terms of companies looking to use innovative CFRP systems. Significant time, research and development effort is required to characterise and develop new systems but if the constituent materials or products evolve it is then unclear if earlier research work remains valid.   Furthermore, the implications of any changes will depend on the particular application, which may or may not be sensitive to particular parameters.   These issues are particularly important in prestressed concrete applications where the CFRP tendons are highly stressed, potentially exposed to demanding environments and expected to maintain their structural integrity over a lifetime that extends to decades. The aim of the current work is to evaluate a series of short-term tests as a means of quality control and/or for the initial assessment of new candidate systems for CFRP pre-tensioned concrete. Cylindrical pultruded CFRP tendons with three different thermoset resin formulations are characterised and assessed. The thermo-mechanical performance metrics that are relevant to force transfer and the long-term durability in wet environments are of particular interest.

Initial characterisation tests are carried out on unexposed tendons to identify the glass transition temperatures and the presence of any internal voids. Uni-axial tendon tensile strengths are measured using either cast anchorage or clamped wedge anchorages. Exposed specimens are used to measure the moisture uptake in the tendons and DNS and torsion tests are undertaken to identify potential changes in the matrix dominated mechanical behaviour of tendons due to exposure to wet environments. Tendons extracted from a prestressed concrete pole that had been highly stressed for 16.5 years (Terrasi *et al*. 2014) provide the context for a discussion of the connection between thermo-mechanical tests and observed in-service behaviour.

2.0 CFRP Tendons for Pretensioned Concrete Applications

Specifications for composites in civil engineering structural systems have been emerging e.g. Bank *et al* (2003). Necessarily such standards make reference to existing standards for FRP composites available from ASTM, ISO, BS EN etc. However, within these standards there can be a bias towards more common laminated ply structures rather than cylindrical pultrusions. One of the challenges with the assessment of unidirectional pultruded systems is that they are very difficult to produce in laboratory conditions unless a pultrusion production line is replicated. The high temperature/pressure and specific matrix flow conditions prevailing in the pultrusion die cannot be achieved or simulated in a simple process such as hand lay-up with vacuum bagging and/or pressure or vacuum injection moulding at the laboratory scale. Therefore the pultrusion curing cycle cannot be exactly reproduced. Furthermore, common additives used in pultrusion such as internal release agents and calcium carbonate (1-2 μm in diameter) can not necessarily be incorporated in laboratory production processes as they can lead to incompatibilities within the matrix system and induce phase separation and precipitation (EMPA (2009)). An additional issue is that hand lay-up layered laminate test specimens designed to mimic pultrusions with similar fibre/resin constituents can suffer from defects between layers. The porosity of laboratory laminated specimens, particularly in the resin rich layer between plies or layers of laminates, can be an order of magnitude higher than that in a pultruded specimen. Porosity is known to influence crucial mechanical properties such as the interlaminar shear strength (ILSS) (Bowles & Frimpong (1992)). So while it is possible to produce a laminate with the same fibre and resin systems as a FRP tendon, the properties of the test specimen will differ from the pultruded product since the surface finishing, curing cycle, lamination etc. will not be the same. The main focus of the current work will therefore be on assessment processes that can be undertaken on commercially produced pultruded cylindrical tendon specimens. To help quantify performance across several competing metrics three different CFRP rod systems will be assessed.

2.1 CFRP prestress tendon characteristics

The CFRP prestress tendons under consideration have a number of characteristics and requirements that make these products distinct from the wider body of composite applications. Of particular note are the tendon geometry, the force transfer e.g. anchorage, bond, and the long-term durability.

Materials with a high strength and stiffness are required which implies a high fibre volume fraction (typically > 0.5). Hence cylindrical pultrusions for prestressed tendons are unidirectional. From geometric and fibre orientation perspectives, CFRP tendons are thus more aligned to FRP concrete reinforcing bars or dowels than laminated cross-ply flat plates. However, prestressed tendon or cable systems are more likely to consist of a series of small diameter cables e.g. between 4 and 6 mm, and so the typical diameter of a tendon will generally be smaller than an unstressed reinforcing bar or dowel. As a result, the tendon diameters can fall outside the remit of existing standards that specifically relate to pultruded rods e.g. ASTM D4476-09 (2009) applies for rods with a diameter > 12.5 mm.   In addition, the initial tendon prestress is often 50-60% of the ultimate tendon failure load and so throughout the lifetime of a structure the tendon will sustain a force in excess of 50% of its breaking stress.

A specific requirement for prestressed concrete with bonded tendons is the need to transfer force through interface shear both in the fabrication and in-service stages.   In pretensioned concrete structures, the tendons need to be anchored temporarily during concrete casting and initial curing. Once the concrete has gained sufficient strength, the stress is released and transferred to the concrete. This introduces the need to grip and sustain the initial prestress force in the anchorage for a period of several days. There must also be sufficient bond between the tendon and concrete in the concrete anchorage zones so that when the stress is transferred, the transfer length is not excessive, this being an area of the structural element in which the shear and bending load carrying capacity is limited by the development of the precompression (Bruggeling (2001), Terrasi *et al* (2012)).

When placed in-service and subjected to applied loads, the tendon force to an extent depends on whether the concrete cracks. If the structure remains uncracked in service, the tendon force away from the anchorage zones should not vary greatly. However, if cracking occurs, there will be a local concentration of stress at the crack locations and this increase will be transferred to the concrete through bond. Excessive bond will lead to a lack of deformability (Lees & Burgoyne (1999)) but sufficient bond is required to ensure small cracks and force transfer between the FRP and concrete. To improve this transfer, the tendons may have an additional surface sand coating to improve bond (Terrasi (2013)).

The in-service exposure conditions of a prestressed concrete structure can be harsh. In outdoor applications, even in European climates the surface temperature of the concrete cover of a CFRP tendon prestressed concrete pole exposed to sun has been measured to be as high as high as 60°C (Terrasi *et al* (2011b)). The internal relative humidity in high performance concrete can reach 87% (Terrasi *et al* (2012)). In marine environments prestressed concrete structures are typically designed to be fully prestressed in service although water can move through the concrete. If cracking takes place under particular service or extreme load combinations the tendons will be further exposed to salt water conditions. These conditions need to be reflected in initial screening tests and one priority is how to combine relatively short-term exposure regimes with mechanical and physical testing that will then be indicative of the long-term in-service performance. In terms of the long-term durability, carbon fibres have generally been found to have very good durability properties (see Mantell (1968)).

However, the epoxy matrix will absorb moisture with time which may influence matrix-dominated properties such as the bond and tendon shear strength (Toumpanaki *et al*. 2014).

2.2 CFRP materials under investigation

The current work explores a series of thermo-mechanical tests as the basis for quality assurance and/or the screening of candidate materials for prestressing applications. The tests are benchmarked by comparing the performance of tendons with three different matrix systems. The three rod systems were Tenax UTS50 systems (F13-12K-800tex or F24-24K-1600tex D) with fibres with a filament diameter of 7μm, a tensile strength of 5100 MPa, Young's modulus of 245 GPa and ultimate strain of 2.1%. The tendon fibre volume fraction was 0.67-68. The EPR 4434/943 and EPR 4434/IPD matrices were a bisphenol-A based low viscosity epoxy resin EPR 4434 combined with either a EPH943 hardener (formulated cycloaliphatic polyamine), or an IPD hardener (cycloaliphatic diamine) at a mix ratio of 100/33pph. An EPR4434 system modified with Nanopox, a masterbatch of SiO_2 nanospheres with diameter 20 nm predispersed in the Bisphenol-A epoxy resin to give a total of 5% of SiO_2 nanospheres by weight, at a mix ratio of 100/36.7/18.5pph was denoted as EPR4434/Nanopox/IPD. The pultrusion cure cycle for all the tendons was 4 minutes at 180°C followed by a proprietary postcure regime. As produced, the tendons had an outer sand coating layer to enhance the bond between the tendon and concrete (Terrasi (2013)). For consistency, in some tests it was necessary to remove this sand coating layer.

3.0 Characterisation of unexposed pultruded tendon material

Initial characterisation tests on dry tendons were undertaken to determine the glass transition temperature (T_g) and to conduct an optical assessment of the cross-section.

3.1 Glass transition temperature T_g (degree of cure, tendon stiffness)

T_g is a parameter where the requirements for FRP tendons for pretensioned concrete applications may be conflicting. An epoxy with a high glass transition temperature, T_g, is desirable to mitigate any reduction in properties when exposed to higher temperatures. But such a material may be more brittle and difficult to anchor (Terrasi *et al* (2011a)). A related consideration is the desirability of a high impact toughness to mitigate the possibility of accidental tendon damage during handling operations in the prestressing plant. A standard method to achieve this is by toughening the tendon's epoxy resin through the addition of microscopic rubber particles. But the presence of these particles has been found to lead to a reduction of the glass transition temperature (Giannakopoulos *et al* (2011)).

The glass transition temperature can potentially give an indication of the extent of curing and the performance in service. A minimum T_g for carbon FRP products with $V_f > 0.5$ has been proposed to be ≥ 93.3°C (Bank *et al* (2003)). However, the value of T_g depends significantly on the method of measurement and the T_g definition used. The glass transition temperature is typically measured using either DMTA (Dynamic mechanical thermal analysis) or DSC (Differential scanning calorimetry) (Sims (2007)). Both methods were used in the current work and the results are reported in **Table 1**. For the DMTA bending mode tests, the sand coating layer was smoothly scratched away from the original rods previously stored in lab conditions and a minimum of two samples were tested. The DMTA T_g values calculated using a E´ (storage modulus) onset definition were fairly similar for all three products (between

121-125°C) but the T_g of the EPR 4434/943 specimens was 10°C lower than the EPR 4434/IPD samples when a tan δ_{max} definition was used. The measured T_g values using DSC ranged from 120 to 135°C and the EPR 4434/IPD results exhibited the greatest variability. The different hardeners and the presence of the filler appeared to have a small influence on the glass transition temperature but there were no clear trends. Differences in the humidity of the samples may be contributing to variations in the results.

3.2 Optical Microscopy

Optical microscopy can be used as a simple and direct quality control procedure for pultruded CFRP rods. The significance of the manufacturing process on the mechanical properties and the durability of FRP rods has been highlighted by several authors (Benmokrane and Mohamed (2013); Toumpanaki *et al*. (2014)). The manufacturing process affects the degree of crosslinking in the epoxy e.g. curing time and temperature and the presence and percentage of voids e.g. die length and heat power, pull out speed. Voids have been observed in commercially available FRP rods (Davalos *et al*. (2008)) suggesting a need for better quality controls. An increase in the moisture uptake in CFRP rods with voids has been reported (Toumpanaki *et al*. (2014)) and voids can aggravate the expected strength reduction of composites under hygrothermal conditions (Zhang *et al*. (2010), Costa *et al*. (2004)). An increase in the void content results in a decrease mainly in the matrix dominated mechanical properties e.g. ILSS (Bowles and Frimpong (1992)) and there is also a dependency on the void geometry and shape.

To detect whether voids were present and to study the fibre distribution, samples of the tendons were cut and prepared for optical microscopy pictures. In **Fig. 1**, optical microscopy pictures from a EPR 4434/943 rod sample are shown relative to a 1000 μm (Fig. 1a), 200 μm (Fig.1b) and 50 μm (Fig.1c & d) scale. There appears to be a solid matrix distribution with no voids. The only abnormalities are small areas of different 'glassy' morphology that are more pronounced in **Fig. 1(d)**, where a dark field is applied for comparison. **Fig. 2** shows a cross-section of a EPR 4434/IPD CFRP rod. A localised void of roughly 303.4 μm is observed near the surface of the sample. **Fig. 2(c)** at a scale of 200 μm reveals a non-uniform fibre distribution with a denser distribution in the brighter areas. A non-uniform fibre distribution was also observed in a CFRP rod with EPR4434/Nanopox/IPD (**Fig. 3**).

4.0 Mechanical performance of unexposed tendons – Uniaxial tension

In terms of strength measures, the determination of the uniaxial tensile strength of a tendon is an important part of a qualification regime for use as FRP reinforcement and prestressing. The tensile strength of a tendon is a fibre-dominated property. However, even with bespoke anchorage systems, when testing CFRP tendons in tension there is a high likelihood of a premature failure in the tendon anchorage due to transverse and shear stresses at the end of the anchorage. In the following, the maximum uniaxial tensile strengths obtained using cast anchorages or short-term tendon clamping anchorage systems are discussed.

4.1 Uni-axial tension tests with cast anchors

Uni-axial tension tests were carried out using resin cast socket anchorages. The cast sockets visible in **Fig. 4(a)** can be either screwed into the machine or clamped. Failures occurred either in the tendon free length or inside the socket, possibly initiated at the end of the cone. The measured tendon strengths using a cast anchorage system (see **Table 2**) were compared with the theoretical values of the tensile strengths of the tendons based on the number of CF-rovings (using a volume fraction of 67% for EPR 4434/943 and 68% for the IPD systems), the fibre strength and an average pultrusion efficiency of 90%. The theoretical strength of the rods should be around 2900 MPa. However, the measured strengths using resin cast anchors were found to be 21.8% to 31.3% lower than the theoretical tensile stress values. The highest measured strength was 2262 MPa for a cast anchorage test on a EPR4434/Nanopox/IPD tendon.

4.2 Uni-axial tension tests with clamped anchors

Clamped wedge anchorage systems are reusable and quick to install. This is particularly advantageous for pre-tensioned concrete where it is only necessary to impart tension into the tendon until the concrete gains sufficient strength for the release of prestress.

Tensile tests with clamped anchorages were undertaken (**Fig. 4(b)**) and the results presented in **Table 2**. The axial strength results using clamped anchorages are consistently lower than the cast anchor results and ranged between 1468 and 1695 MPa. The reduction is postulated to be due to local compressive and shear stress concentrations in the anchor (Terrasi *et al* (2011a)). To characterise the sensitivity of the tendon to clamping forces and inform the design of more efficient clamping geometries, transverse compression tests between two flat plates without sand or two curved plates with sand were undertaken (Terrasi *et al* (2011a)). In these transverse compression tests (see **Fig. 5**), the samples were found to fail due to combined shear and transverse tension. It was observed that the relative trends of the measured transverse compressive strength for the flat and curved plates (**Table 3**) for the EPR 4434/943 and EPR 4434/Nanopox/IPD were broadly consistent with the anchor results.

The EPR 4434/IPD flat plate results had a high standard deviation and while the cast anchorage strength of the 4434/IPD was lower than the Nanopox result, the clamped strength was slightly higher.

5.0 Durability characterisation of exposed tendons

5.1 Moisture uptake

In a concrete application, the full tendon will be exposed at a crack site (if partially prestressed) or at an internal concrete/tendon boundary where moisture has moved through the concrete cover from an external exposure face. One indication of the potential for the matrix to absorb moisture over time is to submerse unstressed cylindrical tendon specimens in water and weigh them periodically. This does not directly replicate the combined in-service exposure and tendon stress conditions. A further difficulty is the need to then identify how/if the moisture uptake relates to tendon performance. However, the simplicity of unstressed full exposure tests is attractive and moisture uptake tests can also be carried out under accelerated conditions.

The outer sand coating layer introduces the potential for variability in the mass uptake readings but the removal of an outer coating raises a question as to whether the outer surface has been damaged. On balance it was deemed preferable to remove the coating to obtain consistent results. Dessicated CFRP tendons were subjected to water exposure at 23°C and 60°C and the mass uptake with time is shown in **Fig. 6**. At 23°C, the measured uptakes in the EPR 4434/943 and EPR 4434/IPD specimens were fairly similar but, at a given time, the uptake in the EPR 4434/Nanopox/IPD tendon was consistently lower. After over four years, the moisture uptake continues to increase but there appears to be a reduction in the slope which would be indicative of pending saturation. At 60°C, all three tendon materials have similar initial mass uptakes with respect to time. The EPR 4434/943 samples were exposed for a longer period (over 2.5 years) and exhibit a mass loss after 1-1.5 years of exposure at 60°C suggesting that the higher temperature and the longer exposure time promote matrix degradation.

For a Fickian prediction of the tendon moisture profile at a given time, the mass at saturation is required. As this is not yet forthcoming then purely for indicative purposes, M_{sat} was assumed as the mass uptake value after 1138 days (~3.1 years) of immersion in water at 23 °C. This then leads to calculated diffusion rates for the 4434/943, 4434/IPD and 4434/Nanopox/IPD tendons of 2.42×10^{-10} cm^2/sec, $3.02\times10^{-10}$$cm^2$/sec and $2.34\times10^{-10}$$cm^2$/sec respectively. The predicted profiles using these diffusion rates for a number of different time intervals (28, 56 and 127 days) have been plotted in **Fig. 7**. Even after 127 days, there is significant non-uniformity in the predicted moisture profile. This has implications in terms of the time-frame for characterisation tests that would reflect any changes in the properties due to exposure.

6.0 Mechanical performance of exposed tendons

Exposure to moisture is likely to have a greater impact on mechanical properties that are dependent on the matrix properties. The in-plane shear strength and interface shear properties tend to be either matrix-dominated, or fibre-matrix interphase dominated since fibre oxidation, sizing, alignment can have a considerable influence on mechanical properties e.g. ILSS. For a CFRP tendon, the longitudinal tensile strength and longitudinal stiffness are generally fibre-dominated. In the following, a general discussion of uni-axial tension testing and short beam shear tests on exposed specimens is presented. Further test protocols suitable for wet specimens with cylindrical geometries, namely double notch shear and torsion tests, are then critically assessed by undertaking experiments on the CFRP tendons with the three different resin formulations.

6.1 Uniaxial tension:

During the production of pre-tensioned elements, the clamped anchorage is temporary and the long-term durability is not a design constraint. However, the tendon then needs to sustain the applied prestress throughout its service life in environmental conditions. Researchers have undertaken tensile tests after exposure to solutions to assess any degradation in the tensile strength due to exposure (e.g. Uomoto, 2001). The difficulty with exposed tensile tests is that, unless the ends are protected, it is impossible to separate the anchorage and exposure effects since any changes in matrix properties will also affect the anchorage. Indeed, Bank *et al* (2003) noted that the testing of exposed tendons in tension may exhibit a matrix failure in the gripping region leading to erroneous lower tensile strength values (due to a reduction in the load transfer mechanism from matrix to fibres.). In certain cases, there may even be a beneficial influence of exposure possibly due to the deterioration of the matrix properties thereby reducing the propensity for shear lag (Scott & Lees 2012). However, in absence of matrix effects, the degradation of the tensile strength in FRP rods due to moisture uptake is not expected to be significant since the fibres dominate the failure mode. Indeed, studies have shown almost no decrease in tensile strength of exposed CFRP tendons in concrete pore solution (Micelli and Nanni (2004), Chen *et al*. (2007)).

6.2 Transverse shear tests

Transverse shear tests have been carried out on exposed GFRP (e.g. Gentry (2011)) or CFRP tendons (e.g. Scott and Lees (2012)). Unstressed CFRP specimens (Scott and Lees (2012)) were loaded transversely with flat plates after exposure to 60 °C water, salt water or concrete pore solutions for 540 days. The peak failure loads of the specimens in water were similar to the unexposed control specimens. However, an average of a 4% or 7% reduction in failure load was noted in specimens exposed to salt solution or concrete pore solution respectively. Differences in stiffness were also observed. Scott and Lees (2012) also undertook short beam tests with rounded loading plates to negate the local stress concentrations induced by the sharp edges of the flat plates. For specimens loaded with rounded plates and a decrease in the delamination stresses in the range of 25-27 % was observed after exposure to water or salt water immersion conditions. Greater reductions were noted in the concrete pore solution tests. Bank *et al* (2003) proposes short beam testing after 28, 56, 112 and 224 days of conditioning to assess the interlaminar (ILSS) shear of an FRP tendon. In an elastic beam in bending, the maximum shear stress is at the neutral axis. From **Fig. 7** it can be seen that in a circular tendon, the moisture profile will potentially be non-uniform along the neutral axis of the beam.

6.3 Double Notch Shear (DNS)

A transverse shear test and a double notch shear (DNS) test measure somewhat different phenomena and each has its strengths and weaknesses. The DNS test is a representation of the interlaminar shear strength and can be adapted to test circular specimens as shown in **Fig. 8**. However, the test has been found to be very sensitive to machine and notch geometry

(Shokrieh and Lessard (1998)) and high local stress concentrations are generated at the notchs (Pettersson and Neumeister (2006)). Recent studies have also shown that DNS performed in tension or in compression can lead to somewhat different results (EMPA unpublished results) and this is assumed to be due to the different stress concentrations around the notch when loaded in tension or in compression.

Since a central plane is being tested, this test will be most meaningful for exposed specimens when the specimens are fairly well saturated, as in the case of ILSS. Otherwise, the moisture profile may be non-uniform along the shear plane of interest. Baseline shear strengths were obtained from the DNS tests on specimens that had been stored in laboratory conditions. These were not pre-dried so there will have been a level of moisture in the samples. The DNS results were compared with tests where the specimens were notched and then immersed in a salt water solution for seven months at 60 °C prior to testing (the results are shown in **Table 4** where the average measured value from 5 samples is presented). The associated mass uptakes at the time of testing are also presented. When 'dry', the filled EPR4434/Nanopox/IPD matrix was found to have an improved performance when compared with the unfilled resins. However, the EPR 4434/943 and EPR 4434/IPD specimens were 15-19% weaker after immersion whereas losses of 28% were noted in the EPR4434/Nanopox/IPD tendons. Hence the post-immersion DNS results of the three materials were similar. The measured strengths did not seem to correlate with the mass uptake since the Nanopox IPD system had the lowest salt water uptake but greatest reduction in DNS.

6.4 Torsion testing (matrix stiffness)

The principles of the ASTM E143–02(2008) and conditioning were combined to develop a screening test for the matrix stiffness. When FRP tendons are circular, they are well-suited to torsion testing as the outer tendon surface saturates most quickly and this is the surface that sustains the highest stress in a torsion test. So the impact of any deterioration in the matrix stiffness should be apparent even after relatively short-term conditioning. Torsion tests (see **Fig. 9**) were therefore carried out on samples that had been immersed in water at 23°C or 60°C. In these tests, a length of tendon was gripped at one end. A lever arm was then clamped to the tendon a set distance away from the grip and weights were applied through the lever arm. Inclinometers were used to measure the relative rotation at each load increment, hence the torsional stiffness response could be measured. The stiffness was measured as an average from three load unload cycles for either one (EPR 4434/943 and EPR 4434/Nanopox/IPD), or two (EPR 4434/IPD) tendon samples. The 'dry' results and the results after exposure to water have been summarised in **Table 5**. Exposed specimens were tested at specified mass uptakes of around 0.5% (0.51% or 0.54%) to provide a common basis for comparison. The shear modulus values after 1240 days are also presented. Even though the moisture profiles (see **Fig. 7iii**) are similar, the 60°C 4434/IPD samples showed a greater loss in stiffness than the equivalent 23°C specimens at 0.54% uptake suggesting temperature causes a greater degradation. The 23°C stiffness reduction of the 4434/943 and IPD specimens after 1240 days was slightly greater than that of the samples tested after 141 or 127 days (−8% vs −11% and +1% vs −4%), whereas the EPR4434/Nanopox reductions were similar after 266 and 1240 days of exposure at 23°C.

7.0 Discussion and benchmarking against in-service performance

7.1 Test protocol evaluation

The test protocols discussed in the current work are summarised in **Table 6**. They have also been rated on a scale from 1 to 3, where 1 is ‘good’, 2 is ‘some value’ and 3 is ‘limited value’, in terms of their suitability for testing cylindrical pultrusions and also in the potential for assessing physical or mechanical implications due to exposure to moisture.

The glass transition temperature is a standard measure but dependent on the test set-up and definition used, and the initial moisture content in the tendons. Optical imaging proved to be a very powerful means to identify voids in a sample and provide insight into the fibre distribution. However, unless there are visible signs of deterioration due to moisture exposure, this method will not reveal indications of detrimental effects on the mechanical properties.   Moisture uptake gives a relative baseline measure to compare different products but correlations with mechanical properties require further development.

Uni-axial tensile tests are fundamentally challenging due to anchorage issues and it is thus difficult quantify the influence of moisture exposure on the tensile strength. DNS samples require careful machining and the fibres can influence the response of the failure plane. The DNS tests did give an indication of strength changes. However, unless saturated, the moisture profile through the cylindrical section is non-uniform so the moisture level across the failure plane will vary. Transverse shear tests including short-beam shear tests are widely used but non-uniformity of the moisture profile and potential fibre-stiffening effects are potential issues. Torsion tests were readily suited to cylindrical specimens and were effective in assessing matrix stiffness changes due to exposure. Further work is required to determine the viability of torsion testing to measure the matrix strength.

7.2 Case study evaluation of long-term performance of a prestressed concrete pole

An opportunity arose to evaluate selected thermo-mechanical methodologies in the context of a retrospective analysis of CFRP tendons from a prototype prestressed concrete lighting pole section that had been under sustained load for 16.5 years. The high strength pole specimen had a wall thickness of 25-27 mm with eight CFRP tendons distributed radially around the central perimeter. The concrete was centrifugally-cast with a minimum cube strength of 115 MPa after 28 days. The CFRP tendons were 3 mm in diameter and were coated with aluminium oxide sand. The tendon tensile strength was 3375 MPa, the Young's modulus was 180.7 GPa and the ultimate strain was 1.87%. Prestress losses were analytically estimated to be 16.8% 28 days after centrifugal casting, while long term prestress losses were estimated to be around 30%.

The pole specimen was left outside under a sustained loading (**Fig. 10** shows the associated loading arrangement and the failed pole) that induced a stress in the lowest tendon of around 2460 MPa at the beginning of testing. Through stress redistribution in the pole this tendon stress increased to approximately 2940 MPa in 15 years. After 16.5 years under a load equivalent to 72% of the short term bending failure load, the pole specimen failed. Full details of the test programme and results can be found elsewhere (Terrasi *et al*, 2014). Intact sections of the tendons were carefully removed from the broken concrete pole and used as test specimens.

When considering the matrix of tests shown in **Table 6**, moisture uptake testing was discounted since the failed tendons had already been subjected to a typical external environment. Furthermore, the tendon diameter is only 3 mm so transverse shear and DNS testing were difficult to undertake with confidence. The focus therefore was on uni-axial tension testing, torsion testing and optical microscopy.

7.2.1 Uniaxial testing

Samples of the same tendon material that had been stored at SACAC Ltd for 18 years in an unstressed 2 m coil in laboratory conditions were tested as control specimens. Previous tensile test results from 1995 on equivalent 3 mm pultruded tendons without sand coating (Terrasi 1998) were also used as comparators.

The samples extracted from the failed pole and the material stored in the laboratory were tested in the same manner and with the same cast anchorage system as in the original tests from 1995. However, for both sets of aged samples, the failure mode changed from tendon failures in the free length observed in 1995 to failures in the socket at the end of the anchorage. The corresponding test results are shown in **Fig. 11**. Changes were made in the preparation of the anchorage to try to eliminate anchorage failures but these were without success. The strain up to failure was monitored in the 1995 tests with an optical extensometer. In the 2015 tests, a mechanical extensometer captured the strain at about 80% of the expected ultimate load prior to the premature failures. Therefore, the strain at failure has been extrapolated in **Fig. 11**. Rather surprisingly, the average elastic modulus of the tendon samples extracted from the failed pole is 3.4% higher and more than two standard deviations above the original 1995 data. The stored samples showed no change in elastic modulus. It is believed that either the aged samples have lost part of their transverse compressive and/or shear strength inducing premature anchorage failure or the potting resin system used for casting the anchorage has changed. The anchorage resin is nominally the identical formulation to that used in 1995 but changes in the products cannot be excluded. A stiffer cast anchorage could induce higher local stress concentrations and also induce premature failure. A further possible explanation would be some minor alignment effects of the carbon fibres due to matrix creep under prestress and sustained loading of 16.5 years. This effect would be consistent with the higher Young's modulus measured in the extracted specimens. Some or all of these factors may explain the early onset of anchorage failures and corresponding reductions in peak strength and strain.

7.2.2 Torsion testing

Torsion testing was conducted on three tendon samples extracted from the failed pole and also three samples from the material stored in lab conditions. Adjustments to the torsion rig (shown in **Fig. 9)** were required to accommodate the smaller diameter tendons. In particular, the diameter of the clamping ring attachment and the weight of the loading lever arm were reduced. The torsion results are presented in **Table 7**.

The measured stiffness of the samples from the pole after long-term sustained loading was on average 4% higher than the lab samples. This is consistent with the trends observed in the elastic modulus results (see **Fig. 11**) where pole samples were also stiffer with the caveat that the axial modulus is dominated by fibre effects. Using lab storage as a baseline reference it appears that exposure to the concrete alkaline environment was not detrimental. The lower shear modulus of the material from the coil in the lab could be connected to the storage conditions . The concrete internal humidity in the high strength concrete used for the prestressed poles could be lower than the relative humidity levels in the lab. Most of the length of the tendon samples removed from the concrete were not in the vicinity of a crack and therefore not directly exposed to environmental conditions. However, the failed pole samples were stored in lab conditions for over a year prior to torsion testing so would have equilibrated to an extent with the moisture content in the laboratory. So deviations in the humidity and thus the moisture content between the 'failed pole' specimens and the lab stored specimens could have contributed to differences in the shear modulus but the extent of this influence is unknown.

7.0 Conclusions

Three CFRP tendons with the same fibres but different resin systems, EPR 4434/943, EPR 4434/IPD and EPR 4434/Nanopox/IPD, were compared across a series of characterisation, thermo and mechanical qualification tests. The glass transition temperature results were found to be inconclusive and depended on the measurement method used and the definition of T_g. Optical imaging indicated voids in the EPR 4434/IPD tendons and non-uniform zones of fibres in both the IPD and Nanopox/IPD tendons. Whereas the EPR4434/Nanopox/IPD moisture uptake was lower than that of the EPR 4434/943 and EPR 4434/IPD tendons at 23°C, the indication is that the uptakes are similar at 60°C. The uptake results also suggested that degradation processes not observed at 23° C could occur after exposure to water at 60°C. Prior to saturation, the concentration profile in a cylindrical specimen is non-uniform and, depending of the test method, this has implications in terms of the moisture conditions across a test plane.

In general, the determination of the uni-axial tensile strength is hampered by difficulties associated with premature tendon failures in the anchorages. The trend of the cast anchor strength results was broadly consistent with the transverse compression strengths of the three materials where the EPR4434/Nanopox/IPD system was strongest. However, with clamped anchors, the EPR 4434/IPD tendon strengths were similar to the Nanopox ones. Reductions of between 17% and 28 % in the tendon DNS strengths were observed due to exposure to salt water solution for 7 months at 60°C. The EPR4434/Nanopox/IPD tendons originally had the highest DNS strength but exhibited the greatest loss due to exposure. Hence, the post-exposure DNS strengths were similar for all three tendon resins. The tendon torsional stiffnesses generally decreased by 4% to 11% after moisture exposure.

The various thermo-mechanical test methods were critically assessed for their suitability for use with cylindrical pultrusions and incorporation of moisture exposure. While T_g measurements, optical images and moisture uptake results allow for a comparison across different materials, the challenge is to connect these to the long-term mechanical performance in-service. This challenge was highlighted in a retrospective analysis of tendon samples removed from a failed concrete pole that had been under sustained load for 16.5 years. Premature anchorage failures were observed in tensile tests. However, the tensile elastic modulus and torsional stiffness measurements suggested that the stiffnesses of the samples from the failed pole were higher than equivalent samples stored in the laboratory.

8.0 Acknowledgements

The authors are very grateful to SACAC Ltd for their technical advice and financial support of the research. Funding from the Onassis Foundation for one of the authors (ET) is also appreciated.

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